

# Quadrupole anisotropy in dihadron azimuthal correlations in central $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV

A. Adare,<sup>13</sup> C. Aidala,<sup>41,42</sup> N.N. Ajitanand,<sup>58</sup> Y. Akiba,<sup>54,55</sup> H. Al-Bataineh,<sup>48</sup> J. Alexander,<sup>58</sup> A. Angerami,<sup>14</sup> K. Aoki,<sup>33,54</sup> N. Apadula,<sup>59</sup> Y. Aramaki,<sup>12,54</sup> E.T. Atomssa,<sup>34</sup> R. Averbeck,<sup>59</sup> T.C. Awes,<sup>50</sup> B. Azmoun,<sup>7</sup> V. Babintsev,<sup>23</sup> M. Bai,<sup>6</sup> G. Baksay,<sup>19</sup> L. Baksay,<sup>19</sup> K.N. Barish,<sup>8</sup> B. Bassalleck,<sup>47</sup> A.T. Basye,<sup>1</sup> S. Bathe,<sup>5,8,55</sup> V. Baublis,<sup>53</sup> C. Baumann,<sup>43</sup> A. Bazilevsky,<sup>7</sup> S. Belikov,<sup>7,\*</sup> R. Belmont,<sup>63</sup> R. Bennett,<sup>59</sup> J.H. Bhom,<sup>67</sup> D.S. Blau,<sup>32</sup> J.S. Bok,<sup>67</sup> K. Boyle,<sup>59</sup> M.L. Brooks,<sup>37</sup> H. Buesching,<sup>7</sup> V. Bumazhnov,<sup>23</sup> G. Bunce,<sup>7,55</sup> S. Butsyk,<sup>37</sup> S. Campbell,<sup>59</sup> A. Caringi,<sup>44</sup> C.-H. Chen,<sup>59</sup> C.Y. Chi,<sup>14</sup> M. Chiu,<sup>7</sup> I.J. Choi,<sup>67</sup> J.B. Choi,<sup>10</sup> R.K. Choudhury,<sup>4</sup> P. Christiansen,<sup>39</sup> T. Chujo,<sup>62</sup> P. Chung,<sup>58</sup> O. Chvala,<sup>8</sup> V. Cianciolo,<sup>50</sup> Z. Citron,<sup>59</sup> B.A. Cole,<sup>14</sup> Z. Conesa del Valle,<sup>34</sup> M. Connors,<sup>59</sup> M. Csanád,<sup>17</sup> T. Csörgő,<sup>66</sup> T. Dahms,<sup>59</sup> S. Dairaku,<sup>33,54</sup> I. Danchev,<sup>63</sup> K. Das,<sup>20</sup> A. Datta,<sup>41</sup> G. David,<sup>7</sup> M.K. Dayananda,<sup>21</sup> A. Denisov,<sup>23</sup> A. Deshpande,<sup>55,59</sup> E.J. Desmond,<sup>7</sup> K.V. Dharmawardane,<sup>48</sup> O. Dietzsch,<sup>57</sup> A. Dion,<sup>27</sup> M. Donadelli,<sup>57</sup> O. Drapier,<sup>34</sup> A. Drees,<sup>59</sup> K.A. Drees,<sup>6</sup> J.M. Durham,<sup>59</sup> A. Durum,<sup>23</sup> D. Dutta,<sup>4</sup> L. D'Orazio,<sup>40</sup> S. Edwards,<sup>20</sup> Y.V. Efremenko,<sup>50</sup> F. Ellinghaus,<sup>13</sup> T. Engelmöser,<sup>14</sup> A. Enokizono,<sup>50</sup> H. En'yo,<sup>54,55</sup> S. Esumi,<sup>62</sup> B. Fadern,<sup>44</sup> D.E. Fields,<sup>47</sup> M. Finger,<sup>9</sup> M. Finger, Jr.,<sup>9</sup> F. Fleuret,<sup>34</sup> S.L. Fokin,<sup>32</sup> Z. Fraenkel,<sup>65,\*</sup> J.E. Frantz,<sup>49,59</sup> A. Franz,<sup>7</sup> A.D. Frawley,<sup>20</sup> K. Fujiwara,<sup>54</sup> Y. Fukao,<sup>54</sup> T. Fusayasu,<sup>46</sup> I. Garishvili,<sup>60</sup> A. Glenn,<sup>36</sup> H. Gong,<sup>59</sup> M. Gonin,<sup>34</sup> Y. Goto,<sup>54,55</sup> R. Granier de Cassagnac,<sup>34</sup> N. Grau,<sup>2,14</sup> S.V. Greene,<sup>63</sup> G. Grim,<sup>37</sup> M. Grosse Perdekamp,<sup>24</sup> T. Gunji,<sup>12</sup> H.-Å. Gustafsson,<sup>39,\*</sup> J.S. Haggerty,<sup>7</sup> K.I. Hahn,<sup>18</sup> H. Hamagaki,<sup>12</sup> J. Hamblen,<sup>60</sup> R. Han,<sup>52</sup> J. Hanks,<sup>14</sup> E. Haslum,<sup>39</sup> R. Hayano,<sup>12</sup> X. He,<sup>21</sup> M. Heffner,<sup>36</sup> T.K. Hemmick,<sup>59</sup> T. Hester,<sup>8</sup> J.C. Hill,<sup>27</sup> M. Hohlmann,<sup>19</sup> W. Holzmann,<sup>14</sup> K. Homma,<sup>22</sup> B. Hong,<sup>31</sup> T. Horaguchi,<sup>22</sup> D. Hornback,<sup>60</sup> S. Huang,<sup>63</sup> T. Ichihara,<sup>54,55</sup> R. Ichimiya,<sup>54</sup> Y. Ikeda,<sup>62</sup> K. Imai,<sup>28,33,54</sup> M. Inaba,<sup>62</sup> D. Isenhower,<sup>1</sup> M. Ishihara,<sup>54</sup> M. Issah,<sup>63</sup> D. Ivanishev,<sup>53</sup> Y. Iwanaga,<sup>22</sup> B.V. Jacak,<sup>59</sup> J. Jia,<sup>7,58</sup> X. Jiang,<sup>37</sup> J. Jin,<sup>14</sup> B.M. Johnson,<sup>7</sup> T. Jones,<sup>1</sup> K.S. Joo,<sup>45</sup> D. Jouan,<sup>51</sup> D.S. Jumper,<sup>1</sup> F. Kajihara,<sup>12</sup> J. Kamin,<sup>59</sup> J.H. Kang,<sup>67</sup> J. Kapustinsky,<sup>37</sup> K. Karatsu,<sup>33,54</sup> M. Kasai,<sup>54,56</sup> D. Kawall,<sup>41,55</sup> M. Kawashima,<sup>54,56</sup> A.V. Kazantsev,<sup>32</sup> T. Kempel,<sup>27</sup> A. Khanzadeev,<sup>53</sup> K.M. Kijima,<sup>22</sup> J. Kikuchi,<sup>64</sup> A. Kim,<sup>18</sup> B.I. Kim,<sup>31</sup> D.J. Kim,<sup>29</sup> E.-J. Kim,<sup>10</sup> Y.-J. Kim,<sup>24</sup> E. Kinney,<sup>13</sup> Á. Kiss,<sup>17</sup> E. Kistenev,<sup>7</sup> D. Kleinjan,<sup>8</sup> L. Kochenda,<sup>53</sup> B. Komkov,<sup>53</sup> M. Konno,<sup>62</sup> J. Koster,<sup>24</sup> A. Král,<sup>15</sup> A. Kravitz,<sup>14</sup> G.J. Kunde,<sup>37</sup> K. Kurita,<sup>54,56</sup> M. Kurosawa,<sup>54</sup> Y. Kwon,<sup>67</sup> G.S. Kyle,<sup>48</sup> R. Lacey,<sup>58</sup> Y.S. Lai,<sup>14</sup> J.G. Lajoie,<sup>27</sup> A. Lebedev,<sup>27</sup> D.M. Lee,<sup>37</sup> J. Lee,<sup>18</sup> K.B. Lee,<sup>31</sup> K.S. Lee,<sup>31</sup> M.J. Leitch,<sup>37</sup> M.A.L. Leite,<sup>57</sup> X. Li,<sup>11</sup> P. Lichtenwalner,<sup>44</sup> P. Liebing,<sup>55</sup> L.A. Linden Levy,<sup>13</sup> T. Liška,<sup>15</sup> H. Liu,<sup>37</sup> M.X. Liu,<sup>37</sup> B. Love,<sup>63</sup> D. Lynch,<sup>7</sup> C.F. Maguire,<sup>63</sup> Y.I. Makdisi,<sup>6</sup> M.D. Malik,<sup>47</sup> V.I. Manko,<sup>32</sup> E. Mannel,<sup>14</sup> Y. Mao,<sup>52,54</sup> H. Masui,<sup>62</sup> F. Matathias,<sup>14</sup> M. McCumber,<sup>59</sup> P.L. McGaughey,<sup>37</sup> D. McGlinchey,<sup>13,20</sup> N. Means,<sup>59</sup> B. Meredith,<sup>24</sup> Y. Miake,<sup>62</sup> T. Mibe,<sup>30</sup> A.C. Mignerey,<sup>40</sup> K. Miki,<sup>54,62</sup> A. Milov,<sup>7</sup> J.T. Mitchell,<sup>7</sup> A.K. Mohanty,<sup>4</sup> H.J. Moon,<sup>45</sup> Y. Morino,<sup>12</sup> A. Morreale,<sup>8</sup> D.P. Morrison,<sup>7,†</sup> T.V. Moukhanova,<sup>32</sup> T. Murakami,<sup>33</sup> J. Murata,<sup>54,56</sup> S. Nagamiya,<sup>30</sup> J.L. Nagle,<sup>13,‡</sup> M. Naglis,<sup>65</sup> M.I. Nagy,<sup>66</sup> I. Nakagawa,<sup>54,55</sup> Y. Nakamiya,<sup>22</sup> K.R. Nakamura,<sup>33,54</sup> T. Nakamura,<sup>54</sup> K. Nakano,<sup>54</sup> S. Nam,<sup>18</sup> J. Newby,<sup>36</sup> M. Nguyen,<sup>59</sup> M. Nihashi,<sup>22</sup> R. Nouicer,<sup>7</sup> A.S. Nyanin,<sup>32</sup> C. Oakley,<sup>21</sup> E. O'Brien,<sup>7</sup> S.X. Oda,<sup>12</sup> C.A. Ogilvie,<sup>27</sup> M. Oka,<sup>62</sup> K. Okada,<sup>55</sup> Y. Onuki,<sup>54</sup> A. Oskarsson,<sup>39</sup> M. Ouchida,<sup>22,54</sup> K. Ozawa,<sup>12</sup> R. Pak,<sup>7</sup> V. Pantuev,<sup>25,59</sup> V. Papavassiliou,<sup>48</sup> I.H. Park,<sup>18</sup> S.K. Park,<sup>31</sup> W.J. Park,<sup>31</sup> S.F. Pate,<sup>48</sup> H. Pei,<sup>27</sup> J.-C. Peng,<sup>24</sup> H. Pereira,<sup>16</sup> D. Perepelitsa,<sup>14</sup> D.Yu. Peressounko,<sup>32</sup> R. Petti,<sup>59</sup> C. Pinkenburg,<sup>7</sup> R.P. Pisani,<sup>7</sup> M. Proissl,<sup>59</sup> M.L. Purschke,<sup>7</sup> H. Qu,<sup>21</sup> J. Rak,<sup>29</sup> I. Ravinovich,<sup>65</sup> K.F. Read,<sup>50,60</sup> S. Rembeczki,<sup>19</sup> K. Reygers,<sup>43</sup> V. Riabov,<sup>53</sup> Y. Riabov,<sup>53</sup> E. Richardson,<sup>40</sup> D. Roach,<sup>63</sup> G. Roche,<sup>38</sup> S.D. Rolnick,<sup>8</sup> M. Rosati,<sup>27</sup> C.A. Rosen,<sup>13</sup> S.S.E. Rosendahl,<sup>39</sup> P. Ružička,<sup>26</sup> B. Sahlmueller,<sup>43,59</sup> N. Saito,<sup>30</sup> T. Sakaguchi,<sup>7</sup> K. Sakashita,<sup>54,61</sup> V. Samsonov,<sup>53</sup> S. Sano,<sup>12,64</sup> T. Sato,<sup>62</sup> S. Sawada,<sup>30</sup> K. Sedgwick,<sup>8</sup> J. Seele,<sup>13</sup> R. Seidl,<sup>24,55</sup> R. Seto,<sup>8</sup> D. Sharma,<sup>65</sup> I. Shein,<sup>23</sup> T.-A. Shibata,<sup>54,61</sup> K. Shigaki,<sup>22</sup> M. Shimomura,<sup>62</sup> K. Shoji,<sup>33,54</sup> P. Shukla,<sup>4</sup> A. Sickles,<sup>7</sup> C.L. Silva,<sup>27</sup> D. Silvermyr,<sup>50</sup> C. Silvestre,<sup>16</sup> K.S. Sim,<sup>31</sup> B.K. Singh,<sup>3</sup> C.P. Singh,<sup>3</sup> V. Singh,<sup>3</sup> M. Slunečka,<sup>9</sup> R.A. Soltz,<sup>36</sup> W.E. Sondheim,<sup>37</sup> S.P. Sorensen,<sup>60</sup> I.V. Sourikova,<sup>7</sup> P.W. Stankus,<sup>50</sup> E. Stenlund,<sup>39</sup> S.P. Stoll,<sup>7</sup> T. Sugitate,<sup>22</sup> A. Sukhanov,<sup>7</sup> J. Sziklai,<sup>66</sup> E.M. Takagui,<sup>57</sup> A. Taketani,<sup>54,55</sup> R. Tanabe,<sup>62</sup> Y. Tanaka,<sup>46</sup> S. Taneja,<sup>59</sup> K. Tanida,<sup>33,54,55</sup> M.J. Tannenbaum,<sup>7</sup> S. Tarafdar,<sup>3</sup> A. Taranenko,<sup>58</sup> H. Themann,<sup>59</sup> D. Thomas,<sup>1</sup> T.L. Thomas,<sup>47</sup> M. Togawa,<sup>55</sup> A. Toia,<sup>59</sup> L. Tomášek,<sup>26</sup> H. Torii,<sup>22</sup> R.S. Towell,<sup>1</sup> I. Tserruya,<sup>65</sup> Y. Tsuchimoto,<sup>22</sup> C. Vale,<sup>7</sup> H. Valle,<sup>63</sup> H.W. van Hecke,<sup>37</sup> E. Vazquez-Zambrano,<sup>14</sup> A. Veicht,<sup>24</sup> J. Velkovska,<sup>63</sup> R. Vértési,<sup>66</sup> M. Virius,<sup>15</sup> V. Vrba,<sup>26</sup> E. Vznuzdaev,<sup>53</sup> X.R. Wang,<sup>48</sup> D. Watanabe,<sup>22</sup> K. Watanabe,<sup>62</sup> Y. Watanabe,<sup>54,55</sup> F. Wei,<sup>27</sup> R. Wei,<sup>58</sup> J. Wessels,<sup>43</sup> S.N. White,<sup>7</sup> D. Winter,<sup>14</sup> C.L. Woody,<sup>7</sup>

R.M. Wright,<sup>1</sup> M. Wysocki,<sup>13</sup> Y.L. Yamaguchi,<sup>12</sup> K. Yamaura,<sup>22</sup> R. Yang,<sup>24</sup> A. Yanovich,<sup>23</sup> J. Ying,<sup>21</sup>  
S. Yokkaichi,<sup>54,55</sup> Z. You,<sup>52</sup> G.R. Young,<sup>50</sup> I. Younus,<sup>35,47</sup> I.E. Yushmanov,<sup>32</sup> W.A. Zajc,<sup>14</sup> and S. Zhou<sup>11</sup>

(PHENIX Collaboration)

- <sup>1</sup>Abilene Christian University, Abilene, Texas 79699, USA  
<sup>2</sup>Department of Physics, Augustana College, Sioux Falls, South Dakota 57197, USA  
<sup>3</sup>Department of Physics, Banaras Hindu University, Varanasi 221005, India  
<sup>4</sup>Bhabha Atomic Research Centre, Bombay 400 085, India  
<sup>5</sup>Baruch College, City University of New York, New York, New York, 10010 USA  
<sup>6</sup>Collider-Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
<sup>7</sup>Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
<sup>8</sup>University of California - Riverside, Riverside, California 92521, USA  
<sup>9</sup>Charles University, Ovocný trh 5, Praha 1, 116 36, Prague, Czech Republic  
<sup>10</sup>Chonbuk National University, Jeonju, 561-756, Korea  
<sup>11</sup>Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, P. R. China  
<sup>12</sup>Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan  
<sup>13</sup>University of Colorado, Boulder, Colorado 80309, USA  
<sup>14</sup>Columbia University, New York, New York 10027 and Nevis Laboratories, Irvington, New York 10533, USA  
<sup>15</sup>Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic  
<sup>16</sup>Dapnia, CEA Saclay, F-91191, Gif-sur-Yvette, France  
<sup>17</sup>ELTE, Eötvös Loránd University, H - 1117 Budapest, Pázmány P. s. 1/A, Hungary  
<sup>18</sup>Ewha Womans University, Seoul 120-750, Korea  
<sup>19</sup>Florida Institute of Technology, Melbourne, Florida 32901, USA  
<sup>20</sup>Florida State University, Tallahassee, Florida 32306, USA  
<sup>21</sup>Georgia State University, Atlanta, Georgia 30303, USA  
<sup>22</sup>Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan  
<sup>23</sup>IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia  
<sup>24</sup>University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA  
<sup>25</sup>Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia  
<sup>26</sup>Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic  
<sup>27</sup>Iowa State University, Ames, Iowa 50011, USA  
<sup>28</sup>Advanced Science Research Center, Japan Atomic Energy Agency, 2-4  
Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan  
<sup>29</sup>Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40014 Jyväskylä, Finland  
<sup>30</sup>KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan  
<sup>31</sup>Korea University, Seoul, 136-701, Korea  
<sup>32</sup>Russian Research Center "Kurchatov Institute", Moscow, 123098 Russia  
<sup>33</sup>Kyoto University, Kyoto 606-8502, Japan  
<sup>34</sup>Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France  
<sup>35</sup>Physics Department, Lahore University of Management Sciences, Lahore, Pakistan  
<sup>36</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA  
<sup>37</sup>Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA  
<sup>38</sup>LPC, Université Blaise Pascal, CNRS-IN2P3, Clermont-Fd, 63177 Aubiere Cedex, France  
<sup>39</sup>Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden  
<sup>40</sup>University of Maryland, College Park, Maryland 20742, USA  
<sup>41</sup>Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003-9337, USA  
<sup>42</sup>Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA  
<sup>43</sup>Institut für Kernphysik, University of Muenster, D-48149 Muenster, Germany  
<sup>44</sup>Muhlenberg College, Allentown, Pennsylvania 18104-5586, USA  
<sup>45</sup>Myongji University, Yongin, Kyonggido 449-728, Korea  
<sup>46</sup>Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan  
<sup>47</sup>University of New Mexico, Albuquerque, New Mexico 87131, USA  
<sup>48</sup>New Mexico State University, Las Cruces, New Mexico 88003, USA  
<sup>49</sup>Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA  
<sup>50</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA  
<sup>51</sup>IPN-Orsay, Université Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France  
<sup>52</sup>Peking University, Beijing 100871, P. R. China  
<sup>53</sup>PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia  
<sup>54</sup>RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan  
<sup>55</sup>RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
<sup>56</sup>Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan  
<sup>57</sup>Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo CEP05315-970, Brazil  
<sup>58</sup>Chemistry Department, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA  
<sup>59</sup>Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA

<sup>60</sup>University of Tennessee, Knoxville, Tennessee 37996, USA

<sup>61</sup>Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan

<sup>62</sup>Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan

<sup>63</sup>Vanderbilt University, Nashville, Tennessee 37235, USA

<sup>64</sup>Waseda University, Advanced Research Institute for Science and Engineering, 17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, Japan

<sup>65</sup>Weizmann Institute, Rehovot 76100, Israel

<sup>66</sup>Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Hungarian Academy of Sciences (Wigner RCP, RMKI) H-1525 Budapest 114, POBox 49, Budapest, Hungary

<sup>67</sup>Yonsei University, IPAP, Seoul 120-749, Korea

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The PHENIX collaboration at the Relativistic Heavy Ion Collider (RHIC) reports measurements of azimuthal dihadron correlations near midrapidity in  $d$ +Au collisions at  $\sqrt{s_{NN}}=200$  GeV. These measurements complement recent analyses by experiments at the Large Hadron Collider (LHC) involving central  $p$ +Pb collisions at  $\sqrt{s_{NN}}=5.02$  TeV, which have indicated strong anisotropic long-range correlations in angular distributions of hadron pairs. The origin of these anisotropies is currently unknown. Various competing explanations include parton saturation and hydrodynamic flow. We observe qualitatively similar anisotropies at RHIC to those seen at the LHC, and when both are divided by an estimate of the initial-state eccentricity, the anisotropies follow a common multiplicity scaling. This scaling is also found to extend to heavy ion data at RHIC and the LHC, where the anisotropies are widely thought to be due to hydrodynamic flow. The results presented here, at much lower collision energy and with a deuteron projectile (instead of a proton), provide important new information for understanding the origin of these new long-range correlations.

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Proton- and deuteron-nucleus collisions at relativistic energies have been studied in order to provide baseline measurements for heavy ion collisions. In  $p(d)$ +A collisions, initial-state nuclear effects are present; however, the formation of hot quark-gluon matter as created in heavy ion collisions is not commonly expected. Recently there has been significant interest in the physics of very high multiplicity events in small collision systems, motivated by the observation of a small azimuthal angle ( $\Delta\phi$ ) large pseudorapidity ( $\Delta\eta$ ) correlation of primarily low  $p_T$  particles in very high multiplicity  $p$ + $p$  collisions at 7 TeV [1]. The correlation strikingly resembles the “near-side ridge” observed in Au+Au at 200 GeV [2, 3]. The initial  $p$ + $p$  result sparked considerable theoretical interest [4–6]. Recently, a similar effect was observed in  $p$ +Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV [7]. Subsequent work removed centrality independent correlations (largely from jet fragmentation) by looking at the difference in correlations between central and peripheral events and has additionally uncovered similar long-range  $\Delta\eta$  correlations on the opposite side ( $\Delta\phi \approx \pi$ ) beyond those expected from fragmentation of recoiling jets measured by ALICE [8] and ATLAS [9]. The effect appears as a longitudinally-extended azimuthal modulation with a predominantly quadrupole component (i.e.  $\cos 2\Delta\phi$ ) and bears a qualitative resemblance in both magnitude and  $p_T$  dependence to elliptic flow measurements in heavy ion collisions, where the large quadrupole modulation is understood to be caused by the initial-state spatial anisotropy followed by a nearly inviscid hydrodynamic expansion [10]. A variety of physical mechanisms have been invoked to explain the observed anisotropies in  $p$ +Pb including gluon satu-

ration [6, 11–13], hydrodynamics [5, 14, 15], multiparton interactions [16], and final-state expansion effects [17].

Previous analyses involving two-particle correlations from  $d$ +Au collisions at RHIC have not indicated any long-range features at small  $\Delta\phi$  [2, 18–20]. However, these measurements involved  $p_T$  selections which emphasize jet-like correlations, rather than the underlying event. Also, Refs. [19, 20] were based on  $d$ +Au collisions recorded in 2003 with a small data sample which limited the statistical significance of the results.

We present here the first analysis of very central  $d$ +Au events to measure hadron correlations between midrapidity particles at  $\sqrt{s_{NN}} = 200$  GeV. The center of mass energy per nucleon is a factor of 25 lower than at the LHC, and another potentially key difference is the use of a deuteron as the projectile nucleus rather than a proton. In Ref. [14], within the context of a Monte Carlo Glauber model, the calculated initial spatial eccentricity of the participating nucleons,  $\varepsilon_2$ , for central (large number of participants)  $d$ +Pb is more than a factor of two larger than in central  $p$ +Pb collisions at LHC energies. We find the initial spatial eccentricity  $\varepsilon_2$  from Monte Carlo Glauber [21] for  $d$ +Au at RHIC energies to be similar to the  $d$ +Pb calculations at LHC energies.

The results presented here are based on 1.56 billion minimum-bias  $d$ +Au collisions at  $\sqrt{s_{NN}} = 200$  GeV recorded with the PHENIX detector in 2008. The event centrality in  $d$ +Au is determined by categorizing the integrated charge by upper percentile as seen by a beam-beam counter (BBC) facing the incoming Au nucleus [22]. Here we isolate a more central sample than previously analyzed, in order to compare more closely to the LHC

results. We use central and peripheral event samples comprising the top 5% and 50–88% of the total charge distributions, respectively.

This analysis considers charged hadrons measured within the two PHENIX central arm spectrometers. Each arm covers nominally  $\pi/2$  in azimuth and has a pseudorapidity acceptance of  $|\eta| < 0.35$ . Charged tracks are reconstructed using the drift chambers with a hit association requirement in two layers of multiwire proportional chambers with pad readout, achieving a momentum resolution of  $0.7\% \oplus 1.1\%p$  (GeV/c). Only tracks with full and unambiguous drift-chamber and pad-chamber-1 hit information are used. Electrons are rejected with a veto in the ring-imaging Čerenkov (RICH) counters.

All pairs satisfying the tracking cuts within an event are measured. The measured pairs are then corrected for the PHENIX azimuthal acceptance through use of mixed event distributions. The conditional yield of pairs is determined by:

$$\frac{1}{N^t} \frac{dN^{\text{pairs}}}{d\Delta\phi} \propto \frac{dN^{\text{pairs}}_{\text{same}}/d\Delta\phi}{dN^{\text{pairs}}_{\text{mix}}/d\Delta\phi} \quad (1)$$

where  $N^t$  is the number of *trigger* hadrons (trigger hadrons are those which have the momenta required to begin the search for a pair of hadrons) and  $N^{\text{pairs}}_{\text{same}}$  ( $N^{\text{pairs}}_{\text{mix}}$ ) is the number of pairs from the same (mixed) events. Mixed pairs are constructed with particles from different events within the same 5% centrality class and with event vertices within 5 cm of each other. Since the focus of this analysis is on the shape of the distributions, no correction is applied for the track reconstruction efficiency, which has a negligible dependence on centrality for d+Au track multiplicities.

In order to make direct comparisons between our measurements and recent ATLAS p+Pb results [9], we follow a similar analysis procedure. Charged hadron selections are made at different momenta from 0.5 through 3.5 GeV/c. For this analysis, each pair includes at least one particle at low  $p_T$  ( $0.5 < p_T < 0.75$  GeV/c) in order to enhance the sensitivity to the nonjet phenomena. The pairs are restricted to pseudorapidity separations of  $0.48 < |\Delta\eta| < 0.7$ , in order to minimize the contribution from small-angle correlations arising from resonances, Bose-Einstein correlations, and jet fragmentation. This pseudorapidity gap is chosen to be as large as possible within the PHENIX tracking acceptance, while still preserving an adequate statistical sample size.

The associated yield due to azimuthally uncorrelated background is estimated by means of the zero-yield-at-minimum (ZYAM) procedure [23]. This background contribution is obtained for both the central and peripheral samples by performing fits to the conditional yields using a functional form composed of a constant pedestal and two Gaussian peaks, centered at  $\Delta\phi = 0$  and  $\pi$ . The

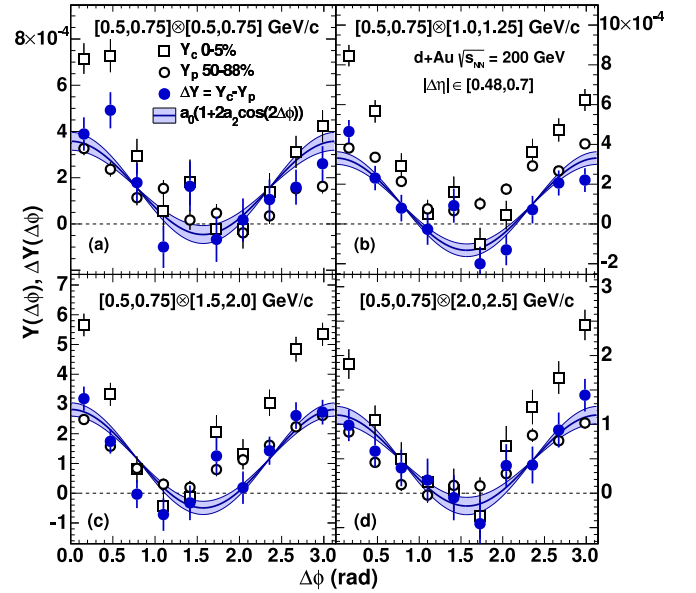


FIG. 1: (color online) Azimuthal conditional yields,  $Y(\Delta\phi)$ , for (open [black] squares) 0–5% most central and (open [black] circles) peripheral (50–88% least central) collisions with a minimum  $\Delta\eta$  separation of 0.48 units. (filled [blue] circles) Difference  $\Delta Y(\Delta\phi)$ , which is ([blue] curve) fit to  $a_0 + 2a_2 \cos(2\Delta\phi)$ , where  $a_0$  and  $a_2$  are computed directly from the data. (shaded [blue] band) Statistical uncertainty on  $a_2$ . No correction for the  $\Delta\phi$  independent reconstruction efficiency has been applied.

minimum of this function,  $b_{\text{ZYAM}}$ , is subtracted from the  $\Delta\phi$  distributions, and the result is  $Y(\Delta\phi)$ :

$$Y(\Delta\phi) \equiv \frac{1}{N^t} \frac{dN^{\text{pairs}}}{d\Delta\phi} - b_{\text{ZYAM}} \quad (2)$$

The conditional yields  $Y_c(\Delta\phi)$  and  $Y_p(\Delta\phi)$  (central and peripheral events, respectively) are shown in Fig. 1, along with their difference  $\Delta Y(\Delta\phi) \equiv Y_c(\Delta\phi) - Y_p(\Delta\phi)$ . As in Ref. [9], this subtraction removes any centrality independent correlations, such as effects from unmodified jet fragmentation, resonances and HBT. In the absence of any centrality dependence,  $Y_c(\Delta\phi)$  and  $Y_p(\Delta\phi)$  should be identical. Due to the limitations of our method, any signal in the peripheral events is subtracted from the central events. We see that  $Y_c(\Delta\phi)$  is significantly larger than  $Y_p(\Delta\phi)$  for  $\Delta\phi$  near 0 and  $\pi$ .

In a manner similar to Ref. [9], we find that the difference with centrality is well described by the symmetric form:  $\Delta Y(\Delta\phi) \approx a_0 + 2a_2 \cos(2\Delta\phi)$  as demonstrated in Fig. 1. The coefficients  $a_n$  and their statistical uncertainties are computed from the  $\Delta Y(\Delta\phi)$  distributions as:  $a_n = \langle \Delta Y(\Delta\phi) \cos(n\Delta\phi) \rangle$ . The  $\cos(2\Delta\phi)$  modulation appears as the dominant component of the anisotropy for all trigger/partner combinations as will be quantified below.

The PHENIX central arm spectrometers lack sufficient  $|\Delta\eta|$  acceptance to completely exclude the near-side jet

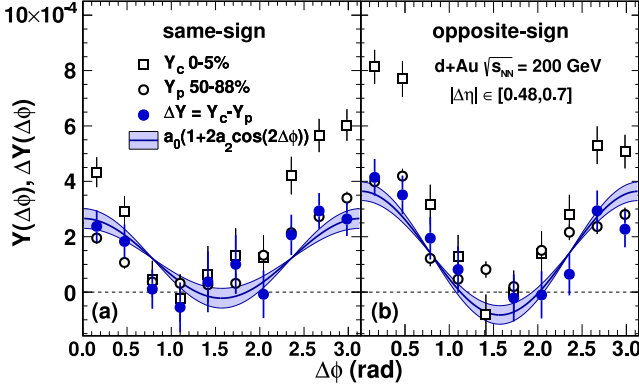


FIG. 2: (color online) Sample comparison of  $Y(\Delta\phi)$  and  $\Delta Y(\Delta\phi)$  for same and oppositely charged pairs for  $1.25 < p_T^a < 1.5$  GeV/c and  $0.48 < |\Delta\eta| < 0.7$ . The symbols, curve, and shaded band are as described in the Fig. 1 caption.

peak. To assess the systematic influence of any residual unmodified jet correlations, we analyzed charge-selected correlations. Charge-ordering is a known feature of jet fragmentation which leads to enhancement of the jet correlation in opposite-sign pairs, and suppression in like-sign pairs, in the near side peak (e.g. Ref. [24]). A representative  $p_T$  selection of  $Y(\Delta\phi)$  and  $\Delta Y(\Delta\phi)$  distributions are shown in Fig. 2, where all charge combinations exhibit a significant  $\cos 2\Delta\phi$  modulation. The magnitude of the modulation is larger in the opposite-sign case, indicating some residual unmodified jet correlation contribution. We also varied the  $|\Delta\eta|$  window which changes the residual jet contribution. Both of these cross-checks are used to estimate the systematic uncertainty, as discussed later.

In order to quantify the relative amplitude of the azimuthal modulation we define  $c_n \equiv a_n / (b_{\text{ZYAM}}^c + a_0)$  where  $b_{\text{ZYAM}}^c$  is  $b_{\text{ZYAM}}$  in central events. This quantity is shown as a function of associated  $p_T$  in Fig. 3 for central (0–5%) collisions.

The centrality dependence will be analyzed in further detail in a forthcoming publication, though we note that we have observed a signal of similar magnitude for the 0–20% most central collisions. The ATLAS  $c_2$  results [9] have a qualitatively similar  $p_T^a$  dependence, but with a significantly smaller magnitude. However, it must be noted that the  $c_2$  values from PHENIX and ATLAS are not directly comparable since  $c_2$  is a function of the  $p_T$  of both particles and the trigger particle  $p_T$  range is not identical in the two analyses. ATLAS has also used a much larger  $\Delta\eta$  separation between the particles.

The  $c_3$  values, shown in Fig. 3, are small relative to  $c_2$ . Fitting the  $c_3$  data to a constant yields  $(6 \pm 4) \times 10^{-4}$  with a  $\chi^2/\text{dof}$  of 8.4/7 (statistical uncertainties only). The current precision is inadequate to reveal the existence of a significant  $c_3$  signal.

In  $p$ +Pb collisions the signal is seen in long range  $\Delta\eta$

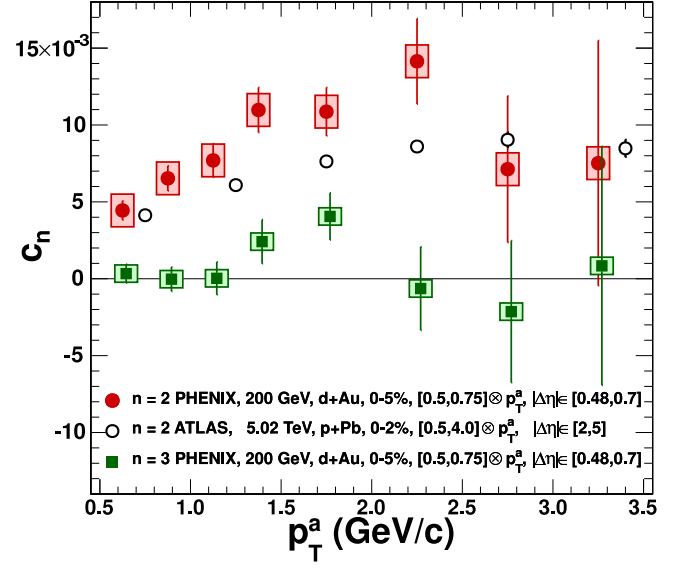


FIG. 3: (color online) The  $n$ th-order pair anisotropy,  $c_n$ , of the central collision excess as a function of associated particle  $p_T^a$ . PHENIX (filled [red] circles)  $c_2$  and (open [black] circles)  $c_3$  are for  $0.5 < p_T^t < 0.75$  GeV/c,  $0.48 < |\Delta\eta| < 0.7$  and ATLAS (filled [green] squares)  $c_2$  [9] are for  $0.5 < p_T^t < 4.0$  GeV/c,  $2 < |\Delta\eta| < 5$ .

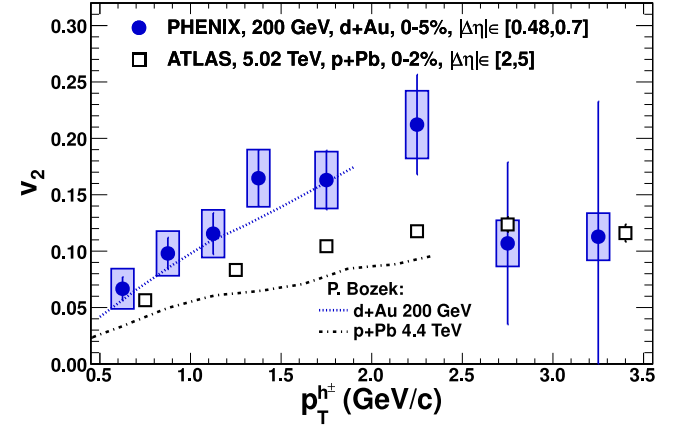


FIG. 4: (color online) Charged hadron second-order anisotropy,  $v_2$ , as a function transverse momentum for (filled [blue] circles) PHENIX and (open [black] circles) ATLAS [9]. Also shown are a hydrodynamic calculation [14, 25] for (upper [blue] curve)  $d$ +Au collisions at  $\sqrt{s_{NN}} = 200$  GeV and (lower [black] curve) 0–4% central  $p$ +Pb collisions at  $\sqrt{s_{NN}} = 4.4$  TeV.

correlations. Here, signal is measured at midrapidity, but it is natural to ask if previous PHENIX rapidity separated correlation measurements [18] would have been sensitive to a signal of this magnitude, if it is present. The maximum  $c_2$  observed here is approximately a 1% modulation about the background level. Overlaying a modulation of this size on the conditional yields shown in Fig. 1 of Ref. [18] shows that the modulation on the near

side is small compared with the statistical uncertainties on the points. In the current analysis, both particles are near midrapidity, while the analysis in Ref [18] includes one of the particles very forward ( $3.0 < \eta < 3.8$ ) in the  $d$ -going direction. Thus, with the current results we cannot determine whether the signal observed here persists for  $\eta > 3$ .

A measure of the single-particle anisotropy,  $v_2$ , can be obtained under the assumption of factorization [26–28], which gives the relation  $c_2(p_T^t, p_T^a) = v_2(p_T^t) \times v_2(p_T^a)$ . We have varied  $p_T^t$  and recomputed  $v_2(p_T)$  and find no significant deviation from this factorization hypothesis. The calculated single particle  $v_2$  is shown in Fig. 4, and also compared with the ATLAS [9] results, again revealing qualitatively similar  $p_T$  dependence with a significantly larger magnitude. We also compare the  $v_2$  results to a hydrodynamic calculation [14, 25] and find good agreement between the data and the calculation, which predicts larger anisotropy in  $d$ +Au than  $p$ +Pb collisions (the calculation for  $p$ +Pb is for 0–4% centrality at 4.4 TeV, not 0–2% central at 5.02 TeV as in the data).

The systematic uncertainties as shown in Figs. 3 and 4 are estimated as the root-mean-squared variation of the same-sign and opposite-sign  $c_n$  measurements about the combined value to reflect the influence of possible remaining jet correlations. This systematic uncertainty is applied symmetrically, since the influence of the jet contribution is not known. As a test, the  $\Delta\eta$  interval was varied from the nominal value of 0.48 to 0.36 and 0.60. The  $c_n$  values remained unchanged within statistical uncertainties, with the qualification that the  $|\Delta\eta| > 0.6$  sample lacks sufficient statistics for a precise comparison at higher  $p_T$ . We also produced  $v_2$  values with different trigger particle momentum selections and found no significant change in the extracted values. Other sources of uncertainty, such as occupancy and acceptance corrections, were also found to have negligible effect on these results.

In order to further investigate the origin of this effect in Fig. 5 we plot the RHIC and LHC results scaled by  $\varepsilon_2$  as calculated in a Glauber Monte Carlo as a function of the charged particle multiplicity at midrapidity. The 0–5%  $d$ +Au collisions at  $\sqrt{s_{NN}} = 200$  GeV have a  $dN_{ch}/d\eta$  similar to those of midcentral  $p$ +Pb collisions at the LHC, while the  $\varepsilon_2$  values for  $d$ +Au collisions are about 50% larger than those calculated for the midcentral  $p$ +Pb collisions. The key observation is that the ratio  $v_2/\varepsilon_2$  is consistent between RHIC and the LHC, despite the factor of 25 difference in collision center of mass energy. A continuation of this same trend is seen by also comparing to  $v_2/\varepsilon_2$  as measured in Au+Au [30–32] and Pb+Pb [33, 34] collisions.

In summary, a two-particle anisotropy at midrapidity in the 5% most central  $d$ +Au collisions at  $\sqrt{s_{NN}} = 200$  GeV is observed. The excess yield in central compared to peripheral events is well described by

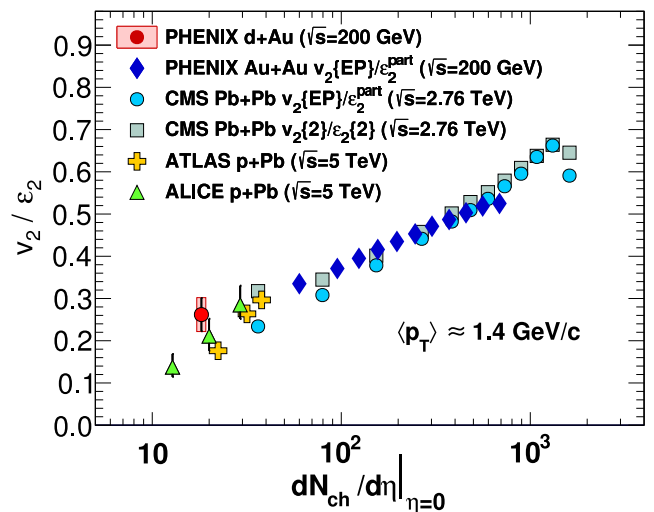


FIG. 5: (color online) The eccentricity-scaled anisotropy,  $v_2/\varepsilon_2$ , vs charged-particle multiplicity ( $dN_{ch}/d\eta$ ) for  $p(d)$ +A collisions measured by PHENIX, ATLAS [9], and ALICE [8]. Also shown are Au+Au data at  $\sqrt{s_{NN}} = 200$  GeV [30–32] and Pb+Pb data at  $\sqrt{s_{NN}} = 2.76$  TeV [33, 34]. The  $v_2$  are for similar  $p_T$  selections. Due to the lack of available multiplicity data in  $p$ +Pb and  $d$ +Au collisions the  $dN_{ch}/d\eta$  values for those systems are calculated from HIJING [29].

a quadrupole shape. The signal is qualitatively similar to that observed in long range correlations observed in  $p$ +Pb collisions at much higher energies, but with a significantly larger amplitude than that observed in 0–2% central  $p$ +Pb collisions at ATLAS. While our acceptance does not allow us to exclude the possibility of centrality dependent modifications to the jet correlations, the subtraction of the peripheral jet like correlations has been checked both by varying the  $\Delta\eta$  cuts and exploiting the charge sign dependence of jet-induced correlations. The observed results are in agreement with a hydrodynamic calculation for  $d$ +Au collisions at  $\sqrt{s_{NN}} = 200$  GeV.

We find that scaling the results from RHIC and the LHC by the initial second order participant eccentricity brings the RHIC and LHC results to a common curve as a function of  $dN_{ch}/d\eta$  also shared by elliptic flow coefficients from Au+Au and Pb+Pb collisions. This finding suggests that these phenomena are sensitive to the initial state geometry and that the same underlying mechanism is responsible in both  $p$ +Pb collisions at the LHC and  $d$ +Au collisions at RHIC. It also suggests a relationship to the hydrodynamic understanding of  $v_2$  in heavy ion collisions. The observation of these correlations at both RHIC and the LHC provides important new information for understanding these phenomena. Models which seek to describe these features must be capable of also explaining their persistence as the center of mass energy is varied by a factor of 25.

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\* Deceased

† PHENIX Co-Spokesperson: morrison@bnl.gov

‡ PHENIX Co-Spokesperson: jamie.nagle@colorado.edu

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